Does the mechanism of decoherence solve the preferred basis problem in the many worlds interpretation?

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1 Introduction

The measurement problem is one of the biggest foundational issues in quantum mechanics. The issue of how and when we transition from a quantum to a classical state, when a measurement is conducted, has been present since quantum mechanics inception. This foundational issue has led to many different interpretations with varying solutions. One of the most popular of these interpretations is the Many Worlds interpretation. This will be the interpretation we focus on and particularly Everett's Relative State formalism.

The preferred basis problem is prevalent in many interpretations of quantum mechanics and is particularly apparent in the many worlds interpretation. The problem in this context is that given that we can decompose a superposition in infinitely many bases, why in the branching of the worlds do we select the position bases or any other particular bases for that matter?

This question is vital to answer as it holds fundamental implications for why in each "world" we see classical results and why we experience the reality we do.

2 Everett's Formulation

Everett's Relative State formulation can be found in more detail in the Stanford Encyclopedia [Bar23]. However, we will give a brief summary here:

Everett's formalism takes the four principles of Von Neuman's standard collapse formulation of quantum mechanics and removes the need for two dynamics by attempting to explain reality with just the unitary evolution of the Schrodinger equation. To reconcile the apparent contradictions with our perception of reality and why we see classical outcomes, Everett suggests that after a measurement the state of the system and observer becomes entangled and each component of the resulting superposition corresponds to one relative state of the observer. Everett uses "the fundamental relativity of states" to express that each definite experience of the observer is described in each relative state of a global superposition.

3 Decoherence as a solution?

Initially environmentally induced decoherence, as defined in Zurek's work [Zur02], would seem to provide a solution. Decoherence manifests itself as the suppression of off-diagonal terms in the reduced density matrix of a system due to interaction with an environment.

For example in a single qubit system where the qubit is coupled to an environment and the qubit is in a superposition:

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

The reduced density matrix would look like:

$$\rho s(t) = \begin{pmatrix} |\alpha|^2 & \alpha\beta^* e^{-\Gamma(t)} \\ \alpha^*\beta e^{-\Gamma(t)} & |\beta|^2 \end{pmatrix}$$

Where as $\Gamma(t) \to \infty$ the off-diagonal terms vanish leaving a classical mixture of states where $|0\rangle$ would have the probability $|\alpha|^2$ and $|1\rangle$ would have the probability of $|\beta|^2$.

In more general terms, decoherence seems to select a preferred basis through repeated interaction with an environment. This selection of a basis would seem to provide a solution to the problem. However, upon a literature review we found disagreement on this, which led us to compare papers on this topic theoretically and in the context of a concrete experiment.

4 Paper Summary

For the paper arguing that decoherence is a viable solution to the preferred basis problem, we selected Wallace's paper "Decoherence and Ontology" [Wal24]. For the paper representing the opposing view, we selected Inamori's paper "No quantum process can explain the existence of the preferred basis: decoherence is not universal" [Ina18].

4.1 Wallace's Paper

In Wallace's paper, he argues that when quantum mechanics is taken seriously and literally, it describes a unitarily evolving wavefunction that contains multiple branches. These branches correspond to different quasi-classical outcomes. He also presents decoherence as an emergent, not fundamental, process that arises from system-environment interactions. He argues that decoherence helps us to understand the appearance of classical worlds, but it does not define a collapse or new law. He explains that decoherence theory shows how interactions with the environment dynamically select a basis. He emphasizes that the selection of the preferred basis is emergent and approximate, not fundamental, but that is completely normal in science and expected for an emergent process.

In the end he concludes:

- At the most fundamental level, the quantum state is all there is.
- As such, Everett's formalism is just Quantum Mechanics.
- Worlds are mutually dynamically isolated structures instantiated within the quantum state, which are structurally and dynamically quasi-classical.
- The existence of worlds is explained by decoherence theory.

4.2 Inamori's Paper

In Inamori's paper, two main arguments are made:

1. That nowhere in the laws of quantum mechanics does it formally obliges the measurement to be done in the basis where we see a classical mixture.
2. That quantum processes such as decoherence make an implicit and unjustified assumption about the initial independence of system and environment. Without this assumption, Inamori demonstrates that decoherence is not guaranteed to lead to a classical mixture of states and therefore cannot solve the preferred basis problem.

From this, Inamori concludes:

- The preferred basis must be a postulate as quantum mechanical processes cannot themselves solve the preferred basis problem.
- That the change of measurement basis is a physical process.

5 Methodology

For the comparison we first started out listing the main arguments made by each author like we have done in the previous section. Once this was complete we applied the key points to the following criteria:

- The comparison must be done in the context of Everett's formalism. This is the formalism Wallace makes his arguments in and to fully explore his arguments we must take them in this context. Inamori's paper claims that no quantum mechanical process can explain the existence of the preferred basis. This is regardless of the interpretation and as such the criticism, if made well, should hold up in this context. This is why we used Everett's Relative state formalism as the background to directly compare the two papers.
- The arguments made must be assessed in isolation before they are fully contrasted and compared. This is to highlight any initial inconsistencies in the points made by the authors.
- The arguments and viewpoints must then be applied to an experimental setting. This is another way to directly compare the different arguments and what they say about reality. This is crucial to not only make the comparison more concrete but also helps expose some of the flaws in the arguments made.

6 Theoretical Analysis

Despite decoherence being an emergent phenomenon from standard quantum mechanics (as discussed in Zurek's work [Zur02]), its application to Everett's relative state formalism remains problematic. Wallace attempts to use decoherence to justify the occurrence of separate physical worlds in Everett's formulation (and thus the solution to the preferred basis problem), but his reasoning is flawed.

Wallace treats the expected ambiguities of an emergent process as a way to dismiss genuine issues, particularly around defining the system-environment split. Although Wallace claims that choosing a "natural" system-environment split yields quasi-classical histories, this lacks any formal foundation, making it unsuitable for a fundamental theory.

Wallace also dismisses the need for an "algorithmic" method to define the split, arguing this aligns with the nature of emergent phenomena. However, the absence of a precise mechanism is a significant weakness in a theory aiming for fundamental explanatory power. Wallace also criticizes the reliance on intuition in evaluating theories, while paradoxically relying on intuitive notions of environments when applying decoherence.

He further caveats decoherence application with knowing the initial state of the system. This is directly challenged by Inamori's paper as an unjustified assumption. Without this, decoherence fails to produce a classical mixture and therefore cannot be used by Wallace to solve the preferred basis problem.

7 Experimental Comparison

To make the comparison more concrete and to hopefully make the flaws of decoherence more apparent we will now apply the comparison to an experimental context. Specifically the electron double slit experiment where photons are used for measurement.

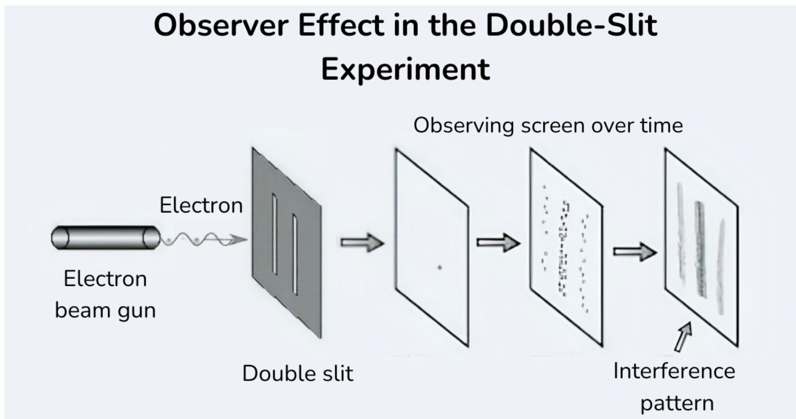

Figure 1: Double Slit Experiment

As figure one demonstrates, without measurement the electrons fired from the double slit produce an interference pattern on the screen. This is because the electrons behave as waves and go through both double slits simultaneously in superposition. The probability amplitudes of each path interfere and produce the pattern. However when we observe the electrons and measure which slit they go through via interaction with photons, we see only two lines.

In the case of a single electron, the photons represent the environment and through interaction with the electron causes it to decohere into a mixture state of either the left or right slit. To be clear this does not solve why we get one outcome over the other only the "options" we can choose from (left or right). In Everett's formalism each one of these outcomes represents a relative state of the observer.

From Wallace's point of view this is exactly what happens. We make a sensible choice of system environment split, apply decoherence and see that we get two possible quasi-classical outcomes. A preferred basis has been selected. However as we discussed before, there is no foundational reason why such a split is made and the only reasoning being it makes sense in the context of the experiment. Not all interactions have such context so we need a formal method to describe this. Other more formal methods have been proposed, however Wallace's insistence that we do not need such an "algorithmic" process causes his explanation to fall short.

From Inamori's point of view applying decoherence here is flawed and not guaranteed to produce this classical mixture of states. This is due to the unjustified assumption about the initial independence of the system and environment. However in this experiments context, it is a much more reasonable assumption given system environment split suggested in the setup. However as mentioned before, this context won't always exist making Inamori's criticism valid.

Lets consider the case where there is initial entanglement between the measurement photon and the fired electron. As demonstrated in Inamori's paper [Ina18] we will no longer get a classical mixture of states. This means that we do not know which slit the electron will pass through as we're no longer left with the "options" of either left or right. This would result in an interference pattern on the screen again despite the fact we observed the electron. However the issue becomes even more apparent with the question: What will our measurement result be as no preferred basis has been selected?

There is no clear answer to this which highlights the flaws of decoherence without the initial assumption of system environment independence.

8 Conclusion

Wallace's defense of decoherence only supports its pragmatic use in identifying quasi-classical behavior, not as a robust solution to the preferred basis problem. The theory merely shifts the issue to selecting the system-environment split, effectively rephrasing the problem rather than solving it. Wallace also relies on the initial independence of the system and environment for his application of decoherence which Inamori demonstrates is unjustified. From this we conclude that decoherence does not solve the preferred basis problem.

References

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